

Dry beneficiation of Slovakian coal

Y. Soong^{*}, T.A. Link, M.R. Schoffstall, M.L. Gray, D.J. Fauth,
J.P. Knoer, J.R. Jones, I.K. Gamwo

*National Energy Technology Laboratory, U.S. Department of Energy, P.O. Box 10940,
Pittsburgh, PA 15236-0940, USA*

Abstract

The dry beneficiation of three types of Slovakian brown coal, namely Ci'gel, Handlova', and Nova'ky coal was conducted via triboelectrostatic separation. Three different types of separators—parallel plate, cylindrical and louvered plate—were used for this study. It was found that a parallel plate separator could reduce the ash contents of Ci'gel and Handlova' coals. The poor quality of separation for the Nova'ky coal studied is probably due to the particle–particle interactions and surface oxidation states of the coal. Published by Elsevier Science B.V.

Keywords: Beneficiation; Triboelectrostatics; Slovakian coal

1. Introduction

The Slovakian brown coal represents one of the important primary resources for power production in Slovakia. The coal is mined in five mines (Handlova', Ci'gel, Dolina, Zahorie and Nova'ky). On average, these coal contain approximately 30% ash and 1.1–1.9% sulfur. Handlova' and Ci'gel coal contain high amounts of toxic elements, especially As, Cd and Hg [1]. Coal from Nova'ky also contains rare organic substances, and elevated levels of ash, sulfur and arsenic [2]. The reduction of emitted oxides of the above components to environmentally acceptable levels could be achieved by using dry or wet pre-combustion and post-combustion cleaning techniques. Under a cooperative research agreement between National Energy Technology Laboratory (NETL) and Slovak Academy of Sciences, NETL has recently completed a study of the application of triboelectrostatic separation to Slovakian brown coals.

Electrostatic beneficiation of coal to remove minerals and sulfur has been investigated widely as an alternate to the expensive post-combustion cleaning technologies [3–13]. Triboelectrostatic beneficiation of coal is a dry method that does not have the disadvantages of wet coal cleaning, subsequent drying, and the processing of accompanying aqueous waste. In this process, coal is ground and then charged by triboelectrification. When two materials are in contact, electrons move until the Fermi levels of two materials at the interface are equalized. The material with a higher affinity for electrons gains electrons and charges negatively, while the material with a lower affinity loses electrons and charges positively. A measure of the relative affinity for electrons is the work function. The values of work function of various compounds in coal such as C, Cu, Al_2O_3 , MgO , and SiO_2 are 4.0, 4.38, 4.7, 4, 5 and 5.4, respectively [11]. Fig. 1 illustrates the principle of a triboelectrostatic separation system for recovering the clean coal. Particles of clean coal (carbon, 4.0 eV) and minerals (SiO_2 , 5.00; Al_2O_3 , 4.7 eV) can be imparted positive and negative surface charges, respectively, with the copper (Cu, 4.38 eV) tribocharger due to differences in the work function values of the particles and the tribocharger, and can be separated by passing them through an external electric field. The differential charging of coal and its mineral impurities, achieved in the triboelectrostatic method, makes it possible to use a static high voltage separator to direct the clean coal and mineral refuse into separate receivers as shown in Fig. 1. Organic (clean coal) particles are attracted to the negative plate, and minerals are attracted to the positive plate. Coal samples deposited on the electrodes as well as those passing through the separation chamber can be collected and analyzed to determine separation efficiency.

This paper presents the results of applying the triboelectrostatic technique to the beneficiation of three types of Slovakian brown coal, namely Ci’gel, Handlova’ and Nova’ky coals.

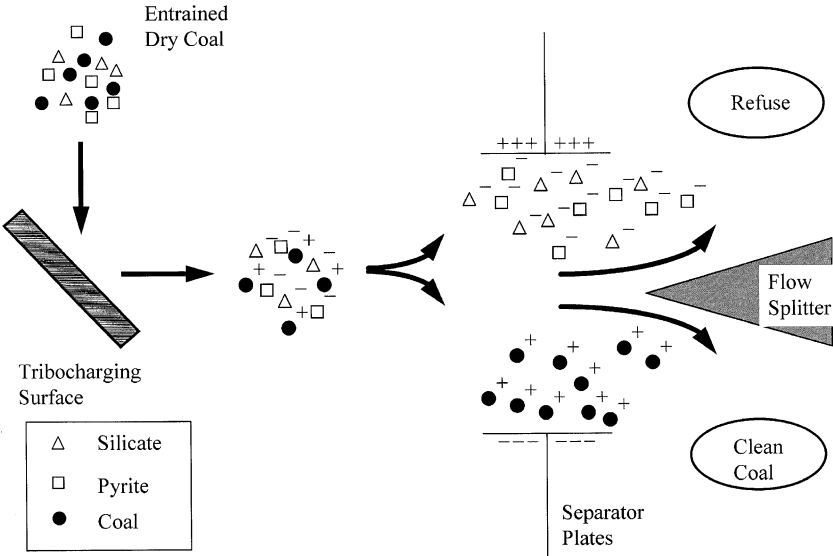


Fig. 1. Principles of triboelectrostatic separation.

2. Experimental

Triboelectrostatic research at NETL has focused on the development of totally pneumatic systems without mechanically rotating or moving devices. Three different types of separators—parallel plate, cylindrical and louvered plate—were used for this study. The parallel plate separator consists of a venturi feed system driven by pressurized nitrogen gas, an injection nozzle, and a high voltage separation section (Fig. 2). The coal particles pass through the venturi feeder and become charged in this turbulent flow zone by contact with the copper tubing and with one another. The contact of the particles with copper surfaces, especially in the turbulent zone of the in-line static mixer, results in effective charging of both coal and mineral impurities. These charged particles are then forced out the nozzle in a ribbon of entrained particles approximately 7.62×0.3175 cm. This plume of particles is directed between two parallel charged plates 15.24-cm long and 7.62-cm apart.

For coal separations, this electric field voltage is + or -25,000 V. The positively charged coal particles are attracted to the negative electrode and the negatively charged mineral particles are attracted to the positive electrode. A splitter is placed 15.24 cm downstream from the nozzle to separate the coal rich and ash rich fractions and direct them to two collection cyclones. The entire separator is swept with laboratory air by applying vacuum to the outlets of the collection cyclones. Sweep flow enters the separator through flow straighteners around the nozzle to control the flow in the separator section. This separator has a capacity of about 8 kg/h in continuous operation and can be used in the batch mode using as little as 100 g of coal feed. The recovery efficiency of the cyclones is typically greater than 90%.

In this work, we used the parallel plate separator to evaluate a variety of feed coals for comparison of performance curves. In this application, separations are done with the injector in three positions with respect to the splitter-centered on the splitter, displaced 0.635 cm toward the positive plate (position left) and displaced 0.635 cm toward the negative plate (position right). The cleaned coals (attracted to the negative electrode), together with the feed, are then analyzed for carbon, ash, and sulfur content to yield a performance curve. These curves can be used to evaluate the potential of coal for separation and to compare the responses of coals from different sources.

The major difference between the cylindrical separator and the parallel plate separator is in the charging and separation zones. In the charging zone, the carrier gas, nitrogen, is delivered through the inner tubing of the two concentric copper tubing (66 cm long), while the coal particle is feed between the inner (I.D. 10.16 cm) and outer tubing (I.D. 15.24 cm). The large flow volume of nitrogen will result in turbulent flow in the coal particle stream, which will generate the frictional/contact between the coal particles and the copper tubing. The separation zone consists of two concentric copper cylinders encased inside plastic tubing. Each of the cylinders is used as an electrode. A cone-shape glassware is placed at the top of inside cylinder to smooth the particles/gas flow stream. In the separation zone, clean coal particles charged positively are attracted toward the outer cylinder. The ash-rich refuse is collected on the inner cylinder (Fig. 3).

The louvered plate separator is similar in construction to that of parallel plate. In the separation zone, it has louvered plates versus that of large plane plates in the parallel

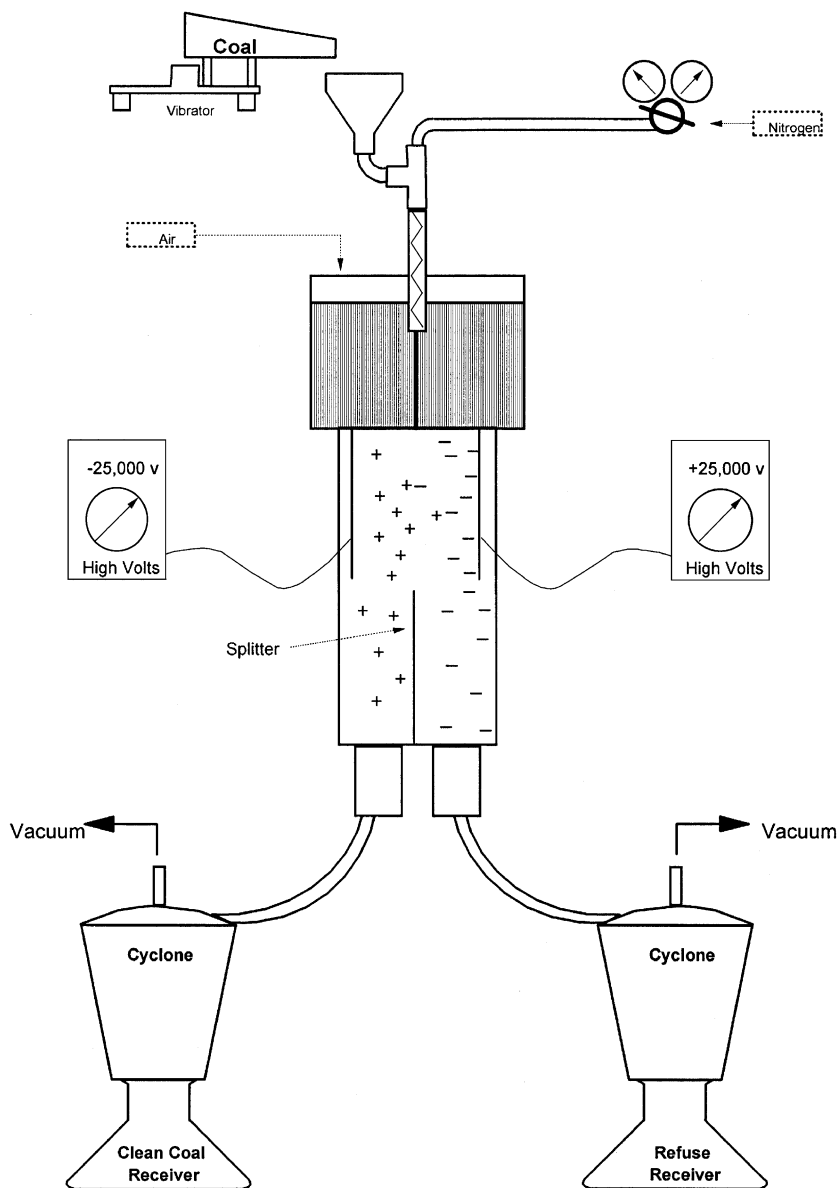


Fig. 2. Schematic diagram of a parallel plate separator.

separator (Fig. 4). After charged in the charging zone, these charged particles then are directed between two louvered charged plates 45.72 cm long and 7.62 cm apart. For coal separations, this unit is operated + or - 25,000 V on the separator plates. The different materials have different work functions and will take on different charges when in contact with the tribocharger. Therefore, the combination of external electric force,

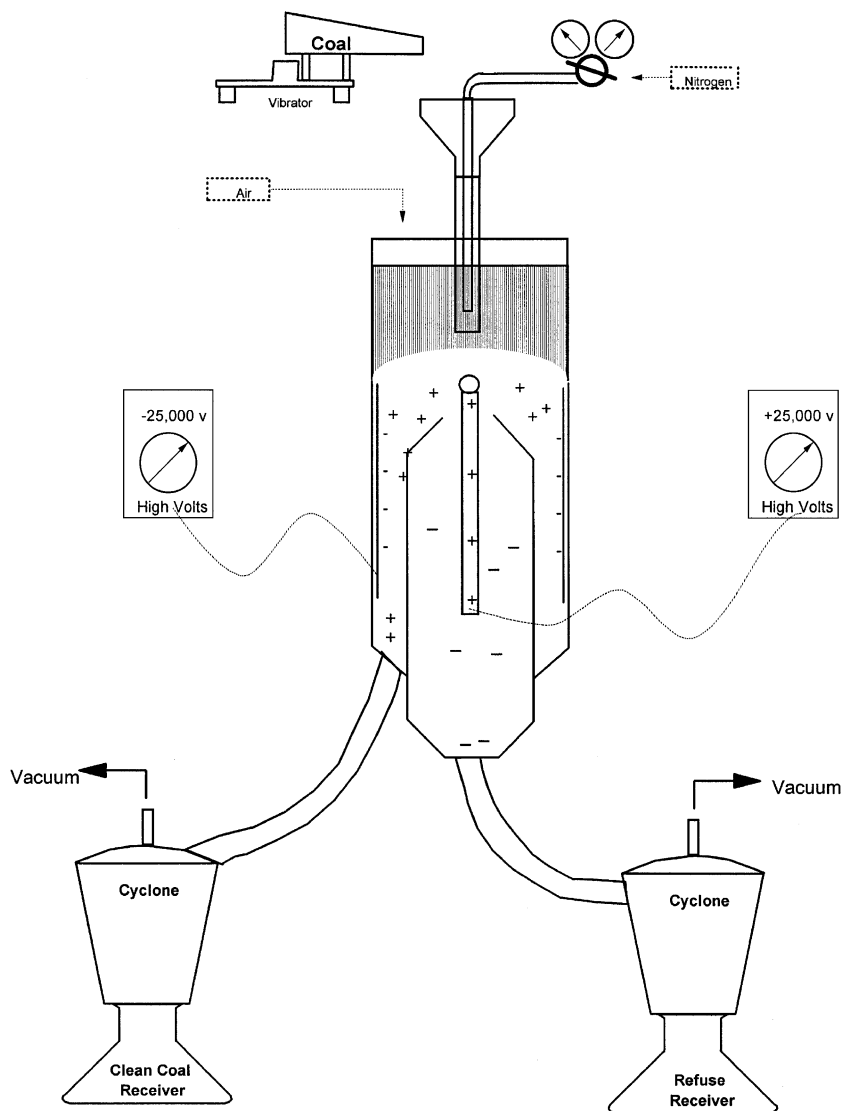


Fig. 3. Schematic diagram of a cylindrical separator.

electron charging to mass ratio, and particle initial velocity will result in different trajectories for different particles. The less dense particles will be deposited on the upper portion of the louvered plate. The more dense particles will be collected on the lower portion of the louvered plate. Those particles that did not charge will go through the center. This separator has a capacity of about 3 kg/h in continuous operation and can be used in the batch mode using as little as 50 g of coal feed. The recovery efficiency of the cyclones is typically greater than 90%.

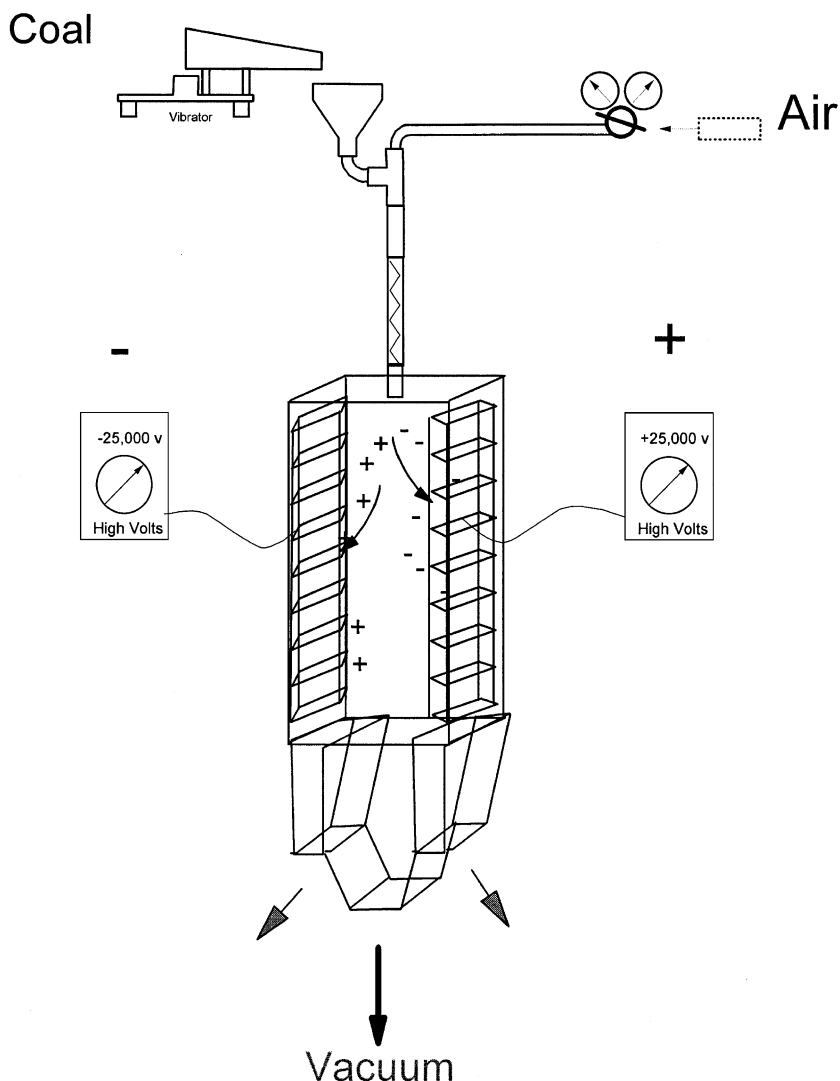


Fig. 4. Schematic diagram of a louvered plate separator.

These three experimental configurations were used to measure the dependence of the separation on three types of Slovakian coal, namely Ci'gel, Handlova', and Nova'ky brown coals. The ground samples supplied by the Slovak Academy of Sciences were tested as received. Using these configurations, these coals were fed through the separator at feed rates varying from less than 454 to more than 4540 g/h. These feed rates correspond to particle-to-gas mass ratios of 0.1–1 g coal/g gas. The carrier gas flow velocity was around 15 cm/sec. The typical operational conditions were at room temperature and the relative humidity around 60%. The clean coal and refuse fractions

were collected on the negative and positive sides, respectively. After collection and homogenization, the fractions were analyzed for sulfur, carbon, and ash content. A thermogravimetric analyzer TGA-601 manufactured by LECO was utilized to determine the moisture, fixed carbon, and ash contents.

3. Results and discussion

The detailed analysis of the Slovakian coals is illustrated in Table 1. Both Handlova' and Ci'gel coals have high ash content, of 52 and 49 wt.%, respectively. The Nova'ky coal has a relatively high sulfur content of 2.62 wt.%, nearly twice that of Handlova' and Ci'gel coals. The moisture content for Nova'ky coal is the highest at 9 wt.% versus 7 and 5.6 for Ci'gel and Handlova' coals, respectively. The recovery of ash on the positively charged refuse side and the recovery of the combustible on the clean coal side from the parallel plate separator for Handlova', Nova'ky and Ci'gel coals are also tabulated in Table 2. The trend of the performance curves for all three coals is similar. The ash content in the refuse is relatively constant around 48 and 28 wt.% for Ci'gel and Nova'ky coal, respectively. For the case of Handlova' coal, the ash content can be increased from 52% of the feed to 58% with the splitter location adjusted to the position center.

The total sulfur content in the separated products can also be seen from Table 2. The sulfur removal is not as impressive on the clean coal side. We have observed a slight

Table 1
Ultimate, mineral, ash, and sulfur analyses on Slovakian coals

	Nova'ky	Ci'gel	Handlova'
Ash (wt.%)	28.24	48.74	51.58
Carbon (wt.%)	41.24	27.66	27.14
Hydrogen (wt.%)	4.19	3.43	3.24
Nitrogen (wt.%)	0.8	0.51	0.35
Oxygen (wt.%)	22.92	18.3	16.22
CaO (wt.%)	2.25	1.47	1.22
MgO (wt.%)	0.62	0.94	0.61
SiO ₂ (wt.%)	17.4	31.7	35.54
Al ₂ O ₃ (wt.%)	4.48	9.49	9.19
Fe ₂ O ₃ (wt.%)	2.44	3.3	3.2
Na ₂ O (wt.%)	0.24	0.3	0.49
P ₂ O ₅ (wt.%)	0.11	0.06	0.04
TiO ₂ (wt.%)	0.13	0.31	0.31
K ₂ O (wt.%)	0.523	1.13	0.93
Volatile (wt.%)	40.18	29.62	26.7
Moisture (wt.%)	9	7	5.6
Total sulfur (wt.%)	2.62	1.37	1.46
Sulfate sulfur (wt.%)	0.33	0.28	0.27
Pyritic sulfur (wt.%)	0.32	0.49	0.45
Organic sulfur (wt.%)	1.96	0.6	0.73

Table 2
Triboelectrostatic separation results

	Feed	C+	C−	R+1/4	R−1/4	L+1/4	L−1/4
<i>Handlova'</i>							
Weight (g)	100	53	37	66	27	22	63
Moisture (%)	5.6	7	9	7	9	9	8
Ash (%)	51.5	58	33	56	31	56	39
Volatile (%)	26.7	23	34	27	35	23	31
Fixed C (%)	16.2	12	24	10	25	12	22
Sulfur (%)	1.46	1.4	1.7	1.4	1.6	1.3	1.6
Recov Com (%)			50		38		78
Recov Ash (%)		60		72		24	
<i>Ci'gel</i>							
Weight (g)	100	59	31	69	22	39	51
Moisture (%)	7	10	12	7.3	12	9	10
Ash (%)	49	48	35	49	33	48	40
Volatile (%)	30	28	34		42	29	36
Fixed C (%)	14	14	19		13	14	14
Sulfur (%)	1.37	1.3	1.6	1.5	1.5	1.2	1.5
Recov Com (%)			39		28		58
Recov Ash (%)		58		70		38	
<i>Nova'ky</i>							
Weight (g)	100	52	35	68	20	24	66
Moisture (%)	9	10	12	10	12	11	12
Ash (%)	28	29	25	28	22	29	23
Volatile (%)	40	38	38	39	40	41	40
Fixed C (%)	23	23	25	23	26	19	25
Sulfur (%)	2.62	2.4	2.7	2.4	2.7	2.3	2.7
Recov Com (%)			36		22		68
Recov Ash (%)		53		67		25	

+ and − for positive and negative plate sides.

C, R, and L are the abbreviation for center, right and left positions of the splitter; 1/4 is 0.635 cm, which is the distance from the center.

increase in the total sulfur content for the clean coal products. This is probably due to the relative high organic sulfur content of the feed. The majority of the total sulfur in the feed coal is organic sulfur (Table 1). The surface organic sulfur groups will be charged positively and collected in the clean coal side. This will result in the increase of the total sulfur content in the clean coal product.

The quality of this triboelectrostatic separation process can be determined by measuring the cumulative recovery of combustible matter and ash as a function of the position of the splitter in the parallel separator. The yield of combustible matter and ash on the clean coal and refuse sides is presented as a percentage of the total amount of each component in the feed. Typical performance curves for Handlova', Nova'ky and Ci'gel clean coals are shown in Fig. 5. The ash contents for the feed are illustrated at 100% combustible in Fig. 5. The recovery of combustible matter in the feed on the negatively charged clean coal side is nearly 78% for Handlova' coal with the splitter

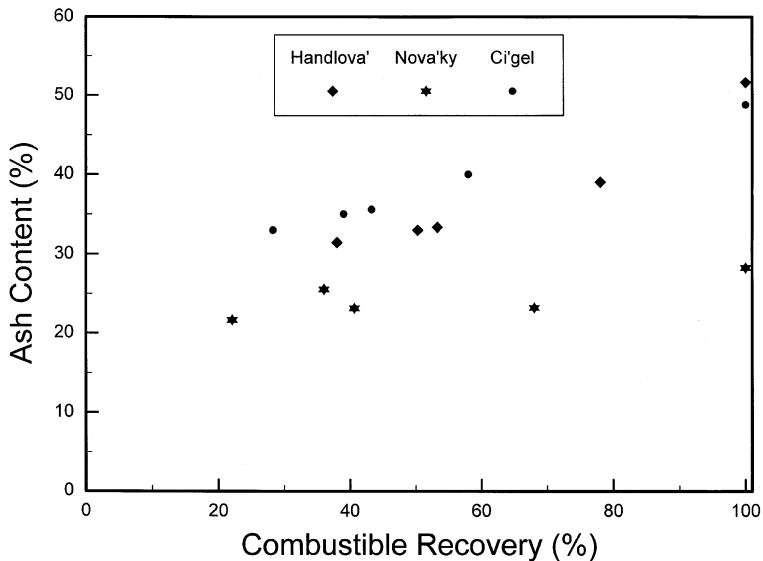


Fig. 5. Combustible recovery versus ash content for clean Slovakian coal (Handlova', ♦; Nova'ky, ★; Ci'gel, ●).

located to the left position. This product, containing 78% of the combustible matter, contains only 39% of the ash, which indicates the selectivity of this process. A continuing decrease in the ash content to 33% is observed as the splitter is moved to the center of the separation chamber; however, the combustible recovery drops to around 50%. Further reducing the ash content to 31% could be achieved by adjusting the splitter to the right position. This significant reduction of the ash content from 52% in the feed to 31% in the product is at the expense of the recovery of the combustible matter. The corresponding combustible recovery for the Handlova' coal is 38%. With this coal the triboelectrostatic separation is particularly effective in removing ash. The trend of the performance curve for Ci'gel coal is similar to that of Handlova' coal. The recovery of combustible matter in the feed on the negatively charged clean coal side is nearly 58% for the Ci'gel coal with the splitter located to the left position. This product contains 40% of the ash with 58% of the combustible matter. Slightly increasing the ash content to around 35% is obtained by moving the splitter to the center of the separation chamber. The combustible recovery is approximately 39%. Further reducing the ash content to 33% could be obtained by repositioning the splitter to the right position. The reduction of the ash content from 49% in the feed to 33% in the clean product is also at the expense of the recovery of the combustible matter. The combustible recovery for this location (position right) is 28% for Ci'gel coal. For the Nova'ky coal, the performance does not appear to be impressive. With this Nova'ky coal, the triboelectrostatic separation is not very effective in removing ash. The ash content could be reduced to 22% from the feed of 28% while the combustible recovery is only 22%.

The results obtained thus far indicate that this is not an exceptional performance for this parallel plate separator. Further, this is a single-pass experiment with no recycle for

recleaning. In an attempt to further reduce the ash content in the clean coal, we have conducted a two-stage separation experiment. The latter uses the clean coal products from the single-stage separation, as the feed for the second stage of separation. Fig. 6 shows the combustible recovery versus ash content for the products obtained from single- and two-stage separation from the parallel plate separator. For Handlova' coal, single-stage cleaning can reduce the ash content to 33 wt.% with 55% recovery of the combustible material. Using the cleaned coal product as the feed for the two-stage separation under the same experimental conditions can further reduce the ash content in the cleaned coal product to 24 wt.% with a 57% recovery (based on the cleaned coal feed) of the combustible material. For the Ci'gel coal, the single-stage separation can reduce the ash content to 35% with combustible recovery of 43%. Two-stage separation can further reduce the ash content to 28 wt.% with up to 60% recovery (based on the cleaned coal feed) of the combustible material. For Nova'ky coal, the two-stage cleaning process does not significantly improve the quality of the separation. The two-stage separation can only reduce the ash content from 26 to 22 wt.% while the recovery of combustible increases from 36% to 56% (based on the cleaned coal feed).

Although the parallel plate separator appears to be widely applicable to different coals, they do respond differently to triboelectrostatic separation. The separation of a 52% ash Handlova' and a 49% ash Ci'gel coal indicated that both coals could be potentially beneficiated via triboelectrostatic methods. The quality of separation for the high ash Handlova' and Ci'gel coal is better than that of low ash Nova'ky coal. The performance of the parallel plate separator does not show quality separation for the low ash Nova'ky coal. This poor response could be related to several factors—relative high

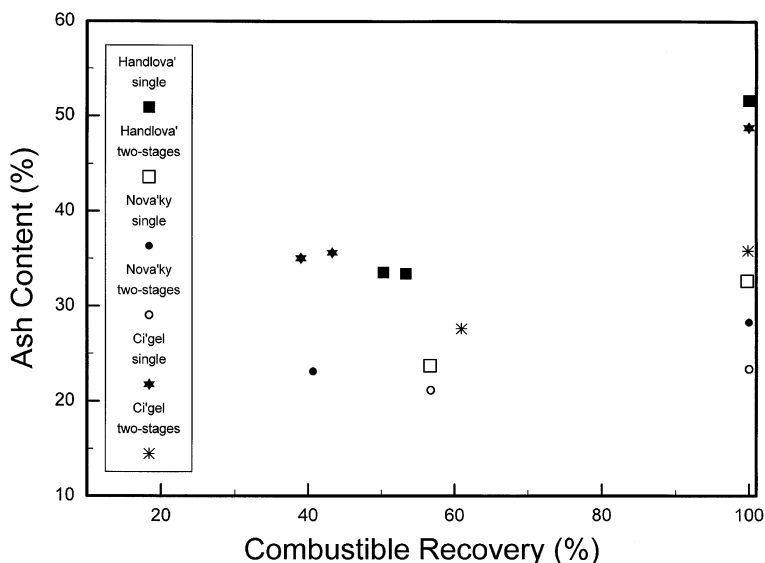


Fig. 6. Combustible recovery versus ash content for single- and two-stage (Handlova' single-stage, ■; Handlova' two-stage, □; Nova'ky single-stage, ●; Nova'ky two-stage, ○; Ci'gel single-stage, ★; Ci'gel two-stage, *).

moisture, particle size, incomplete mineral liberation, some particle charging reversal, particle–particle interactions, and surface oxidation of the coal.

The recovery indicated by the Nova'ky coal data is low and could be due to the fact that the particle size might be large, reducing the amount of mineral impurity liberated from the combustible matrix. The particle size influences the liberation of the mineral matter, the charging efficiency, and the response of the particle to the electrostatic force in the separator. In order to determine the potential for beneficiation by triboelectrostatic means, we conducted screening tests of the as-received coals. Almost 99% of the feed coal samples passed the 200-mesh size screens. Furthermore, a series of microtrac particle size analyses were conducted on the as-received coal samples. They all showed similar bimodal distribution of particle sizes. The average particle sizes are 20, 15 and 12 μm , respectively for Handlova', Ci'gel and Nova'ky coal. It is worth mentioning that the Novaky' coal shows a stronger hydrophobic property than the other two coals studied.

The moisture content of the feed coals might affect the quality of separation. These contents are 5.6, 9 and 7, respectively, for Handlova', Nova'ky and Ci'gel coals. To further reduce the moisture content from the feed, these three coals were dried in the oven at 105°C for 2.5 h prior to separations. After the drying procedure, the moisture content was reduced to approximately 0.6 wt.% for all coals studied. Fig. 7fig shows the combustible recovery versus ash content for coals as received and dried Slovakian coals. For the cases of Handlova' and Nova'ky coals, no significant improvement in the quality of separation is observed. For the Ci'gel coal studied, after the drying process, the ash content in the clean coal is 33 wt.% versus that of 36 wt.% in the absence of drying

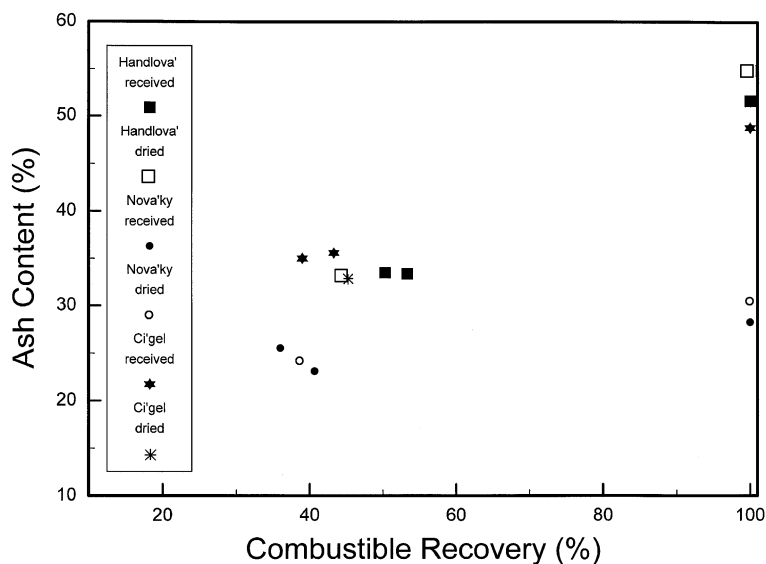


Fig. 7. Combustible recovery versus ash content for as received and dried feed (Handlova' received, ■; Handlova' dried, □; Nova'ky received, ●; Nova'ky dried, ○; Ci'gel received, ★; Ci'gel dried, *).

process. From this experiment, it is concluded that the moisture content in the feed does not significantly contribute to the quality of the separation.

It is also speculated that particle–particle interactions may also play an important role in the separation. We assume just two phases, organic and mineral, one which charges positively on wall collisions and the other which charges negatively on wall collisions. Under turbulent flow conditions, with high particle concentrations, particle–particle collisions can also contribute to the overall charging. In a two-phase system, collisions between particles of a dissimilar phase result in the same final charge as particle wall collisions. Collisions between particles of the same phase, which result in exchange of charge, require that one of the two colliding particles acquires a charge opposite to that resulting from a wall collision.

The charging events represented do not include collisions when one or more of the particles are already charged. A number of references discuss the fundamental processes involved in the triboelectrostatic charging of particles but these fundamental processes are not sufficient to predict the behavior of complex, multiphase systems like coal. For the low ash Nova'ky coal, the organic phase is being deposited on the positive plate and the simple model indicates that the only way this can occur is by having particle–particle collisions between organic as an important charging event. This observation of coal particles on the positive plate suggests that the contribution from the particle–particle collisions cannot be ignored [7].

This model is also consistent with the data for the high ash Handlova' and Ci'gel coal. In both cases, because of the high ash content, increasing particle–particle collisions will increase organic/mineral collisions, which would result in a positive charge for the organic and then still report to the negative plate. It is still not clear why two identical particles will exchange charges after collision, and why the polarity of charge often depends on the particles. The mechanism of charging coal and mineral particles is complicated by the wide range of effective work functions of these particles and the interparticle collisions between these particles during charging and separation processes.

During our previous work on triboelectrostatic separation, we have noticed that the quality of separation for fresh ground coal is much better than that of coal being ground days earlier. Oxidation of the coal surfaces is also thought to be hindering the tribocharging process [6]. All coal carbon should ideally adopt a positive charge for electrostatic beneficiation. The tendency of liptinite and inertinite to exhibit bipolar charging may be related to their unique chemical structure [14]. If the coal powder is exposed to air, then surface oxidation reduces the tendency of carbon to charge positively. The di-oxygen molecule is paramagnetic, and thus has a very low activation energy to form bonds with free radicals present on the coal. Surface peroxides thus formed may accept electrons during tribocharging to decrease the positive charge character of the coal carbons. In addition, the surface peroxides will undergo further reactions to yield a variety of oxidized carbon functions, which may contribute to the altered charge properties. Bailey [15] concluded that the contacted charge exchange is sensitive to the oxidative states of the particle surface.

The effects of tribocharger geometry (parallel plate, cylindrical, and louvered plate separators) was also evaluated for Handlova' coal. Typical performance curves for

parallel plate, cylindrical and louvered plates are illustrated in Fig. 8. For the parallel plate separator, the recovery of combustible matter in the feed on the negatively charged clean coal side is nearly 78% along with 39% of ash for Handlova’ coal with the splitter located to the left position. A continuing decrease in the ash content to 33% is observed as the splitter is moved to the center of the separation chamber; however, the combustible recovery drops to around 50%. Further reducing the ash content to 31% with 44% combustible recovery could be achieved by adjusting the splitter to the right position. For the cylindrical separator utilized, the clean product containing 38% of ash contents, the combustible recovery is around 39%. For the louvered plate separator, the clean coal contains 33% of ash at the lowest combustible recovery of 25%. Among the separators studied, the parallel plate can achieve the lowest ash content with a relative high combustible recovery in the clean product. The louvered plate separator can provide close to the lowest ash content but with the lowest combustible recovery in the clean product. The quality of separation for the cylindrical separator lies between the parallel plate and louvered plate separators. For the parallel plate and louvered plate separators, the electric field in the separation zone is uniform. The electric field in the cylindrical separator is not uniform, but a gradient field that is much stronger at the inner cylinder than at the outer cylinder is produced. The electric field, the carrying gas and other separator design factors might result in the differences in the quality of separation. Therefore, the quality of separation was found to be directly related to the separator utilized. The results obtained from this study agree with those reported by Finseth et al. [7–9] for the Pittsburgh coal.

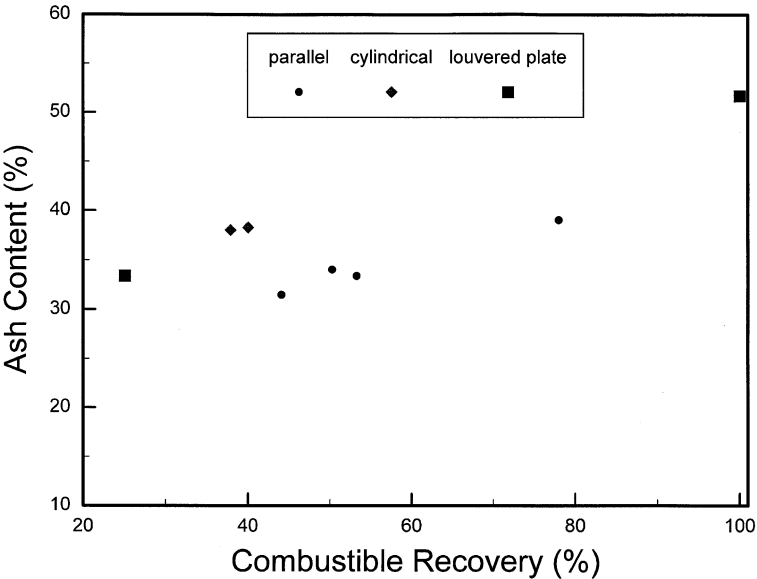


Fig. 8. Combustible recovery for Handlova’ coals under different separators (parallel, ●; cylindrical, ◆; louvered plate, ■).

4. Conclusion

The preliminary data obtained from Slovakian coal separation indicate that simple parallel plate triboelectrostatic separator has the potential to reduce ash contents from Ci'gel and Handlova' coals. The degree of ash removal and combustible recovery was found to be dependent on the type of coal and the configuration of the separator utilized. The separators used in this study cannot qualitatively provide a separation for Nova'ky coal. It is probably due to the nature of the Nova'ky coal, the particle-particle interactions, and the surface oxidation state of the coal. A simple parallel plate separator can quickly evaluate the response of a given coal to this beneficiation approach. The two-stage processes can further reduce the ash content from the products generated from the single-stage cleaning process.

References

- [1] A. Klukanova, S. Rapant, J. Geochem. Explor. 66 (1999) 299.
- [2] L. Tureaniová, P. Balaz, F. Boroska, J. Lipka, Proc. 13th Int. Pgh. Coal Conference. 1996, p. 911.
- [3] N.C. Lockhart et al., Powder Technol. 40 (1984) 17.
- [4] D. Gidaspow, D. Wasan, Y.T. Saxena, R. Gupta, A. Mukhenjee, AIChE Symp. Ser. 83 (255) (1984) 74.
- [5] S. Masuda, T. Makto, T. Takahashi, K. Haga, Y. Tani, Power Technol. 40 (1984) 789.
- [6] T.A. Link, et al., Initial Study of Dry Ultrafine Coal Beneficiation Utilizing Triboelectric Charging with Subsequent Electrostatic Separation, DOE/PETC/TR-90/11 (1990) 19.
- [7] D.H. Finseth, T. Newby, R. Elstrodt, 9th U.S.-Korea Joint Workshop on Coal Utilization Technology, 1992, p. 221.
- [8] D.H. Finseth, W. Gerstler, 10th Korea-USA Joint Workshop on Coal Utilization Technology, 1994, p. v-5.
- [9] D.H. Finseth, K.J. Champagne, M.L. Gray, R. Satler, The 12th Korea-US Joint Workshop on Energy and Environment, 1997, p. 268.
- [10] S.C. Kim, N.W. Son, D.H. Kim, J.G. Oh, The 12th Korea-US Joint Workshop Energy and Environment, 1997, p. 308.
- [11] X.F. Wang, Proceeding Pittsburgh Coal Conference, 1993, pp. 211-216.
- [12] J.M. Stencel, J.L. Schaefer, H. Ban, T.-X. Li, J.K. Neathery, Coal Prep. 19 (1998) 115.
- [13] J.M. Stencel, J.L. Schaefer, H. Ban, T.-X. Li, J.K. Neathery, Proc. ICCS 97, vol. III (1997) 1911.
- [14] M.K. Mazumder, K.B. Tennal, D. Lindquist, J. Electrostat., Inst. Phys. Conf. 143 (1995) 385-392.
- [15] A.G. Bailey, J. Electrostat. 30 (1993) 167.